Modelling of EUV and soft X-ray spectra for nonequilibrium plasma with high energy electrons

Vasily Zakharov*, *Sergey Zakharov, Peter Choi

zakharovvas@gmail.com

EPPRA sas, Courtaboeuf, France

in collaboration with ***Keldysh Institute of Applied Mathematics, Russia***

SEVENTH FRAMEWORK PROGRAMME

Marie Curie Action

European Pulsed Power Research APPLICATIONS

ОРДЕНА ЛЕНИНА им.М.В.КЕЛДЫША РАН

Fluid, Ions and Radiation Ensemble in Integrated Plasma Modelling (FIRE)

UCD DUBLIN

2010 International Workshop on Extreme Ultraviolet Sources

University College Dublin

November 13 - 15, 2010

Abstract

The soft X-ray radiation in water window region can be produced from 2p-1s and 3p-1s resonant transitions in **nitrogen** ions. In EUV range, an emission at 2% band 13.5 nm may be obtained from 5p-4d resonant transitions in **Xe XI** and from the set of satellites and resonant transitions in highly charged **Xe XVII - Xe XXXV** ions as well. Such highly charged ions have a high ionization potential in comparison with plasma temperature in most of laboratory plasmas. Fast electrons generated in different types of nonequilibrium plasma like discharge, solar, laser etc at relatively small portions may have a significant influence on level populations and produce highly charged ions, thus the line emission intensities, despite on low plasma temperature. In the report the influence of fast electrons on the line emission from xenon and nitrogen ions is considered and the maximum emission conditions are explored. Fast electrons distribution functions are added into impact processes kinetics based on the distorted waves approximation with Hartree-Fock-Slater quantum-statistical model. In particular, conditions for highly charged **Xe** ions generation and increase of the emission in the 13.5 nm EUV range are found. The emission at water window band from **nitrogen** plasma may be increased substantially in a narrow range of parameters also. Efficiency of discharge- and laser- produced plasma soft X-ray and EUV sources in required narrow bands is discussed.

Non-Equilibrium Model

System of kinetic equations

Relative populations of levels is described by next system of kinetic equations

$$\frac{dn_\mu}{dt} = \sum_{\nu\neq\mu}^{\nu} n_\nu \alpha_{\nu\to\mu}(N_i, N_e, T, \rho, F) -$$

$$- n_\mu \sum_{\nu\neq\mu}^{\nu} \alpha_{\mu\to\nu}(N_i, N_e, T, \rho, F), \qquad \sum_{\mu} n_\mu = 1,$$

$\alpha_{\nu\to\mu}$ and ***$\alpha_{\mu\to\nu}$*** - total rates of the processes leading to increase and decrease of the level ***μ*** population ***n_μ***, ***N_i*** and ***N_e*** – number of ions and electrons, ***T*** – temperature, ***ρ*** – density. Total rates include a different set of processes depending of model, kind of modelling etc.

In general case, if ***N_e*** is not desired,

$$N_e = Z_0 N_i, \qquad Z_0 = \sum_{\mu} z_\mu n_\mu,$$

z_μ – charge of the ion of level ***μ***, ***Z_0*** - average charge

Electron distributions

Fast Electrons accounting

Distribution of electrons by the energy ***F(T,E,ε)*** with the presence of nonthermal (fast) electrons depends on the energy ***E*** and concentration ***ξ*** of fast electrons.

For the estimation and calculations with nonthermal electrons, the next two Maxwellian distribution function was used

$$F(T,E,\varepsilon)=(1-\xi)F_0(T,\varepsilon)+\xi\,\mathrm{F}_0(E,\varepsilon)$$

F_0 is the Maxwellian distribution:

$$F_0(T_0,\varepsilon)=\frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\,T_0^{-3/2}\,e^{-\varepsilon/T_0},$$

ξ is the relative concentration of fast electrons,
E is the average energy of fast electrons,
T is the electron temperature.

Rate coefficients

Rate coefficients with fast electrons

The impact rate for the ion in the single-electron state $\boldsymbol{\mu}$ with the electron distribution including nonthermal electrons may be disjointed on two parts:

with the thermal colliding electron
&
with the fast one

$$\alpha_\mu = n_\varepsilon \int F(T,E,\varepsilon)\sqrt{2\varepsilon}\,\sigma_\mu(\varepsilon)\,d\varepsilon =$$

$$= n_\varepsilon(1-\xi)\int F_0(T,\varepsilon)\sqrt{2\varepsilon}\,\sigma_\mu(\varepsilon)\,d\varepsilon \; +$$

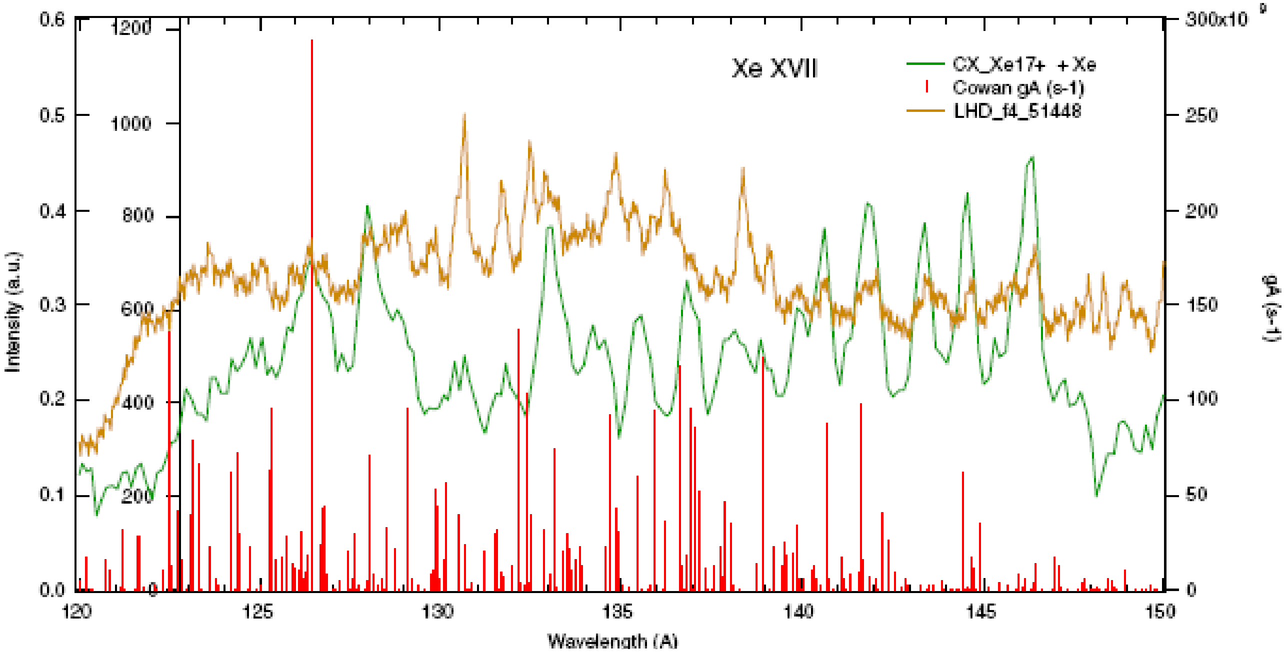
$$+ n_\varepsilon\,\xi \int F_0(E,\varepsilon)\sqrt{2\varepsilon}\,\sigma_\mu(\varepsilon)\,d\varepsilon$$

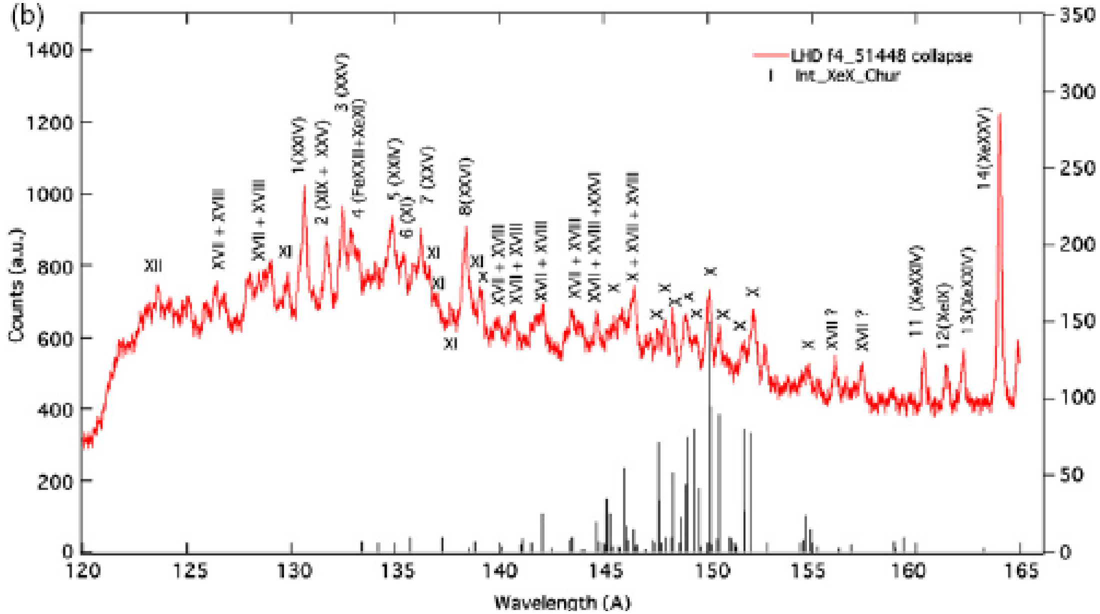
Rates of radiative process were calculated in Kramers approximation by the same way where it was necessary.

Xenon revisited

Experimental data

T Kato et al. J. Phys. B: At. Mol. Opt. Phys. 41 (2008)



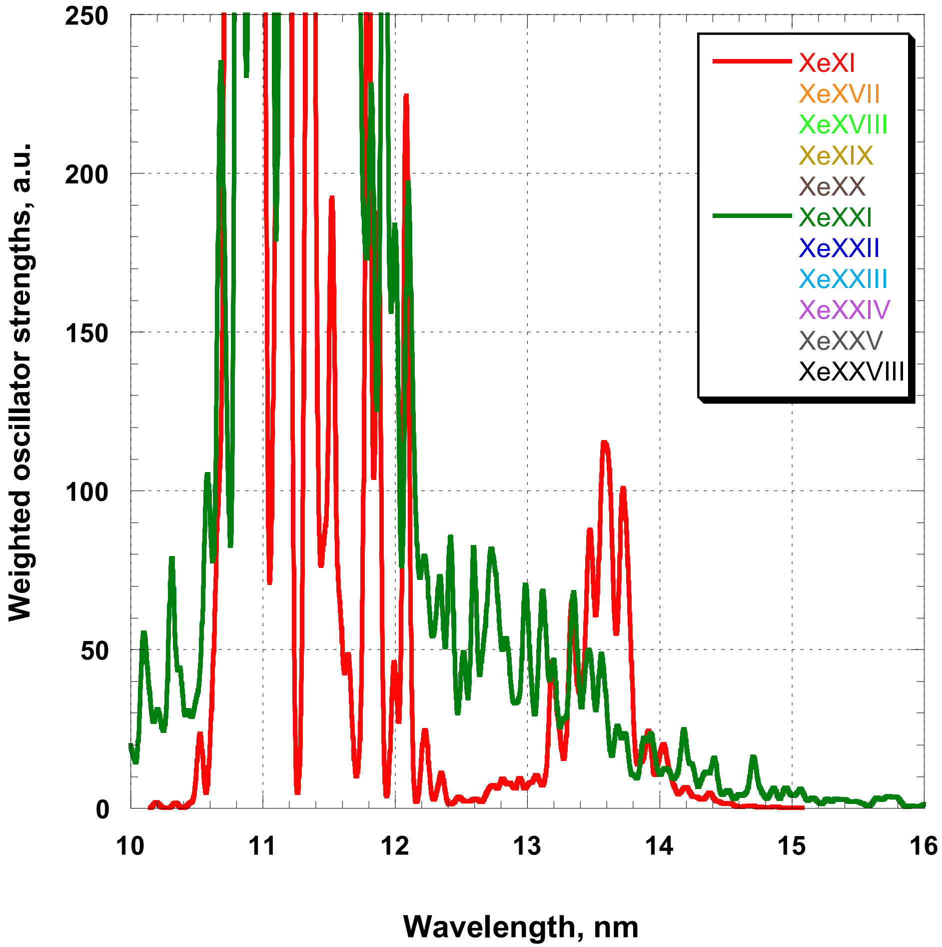


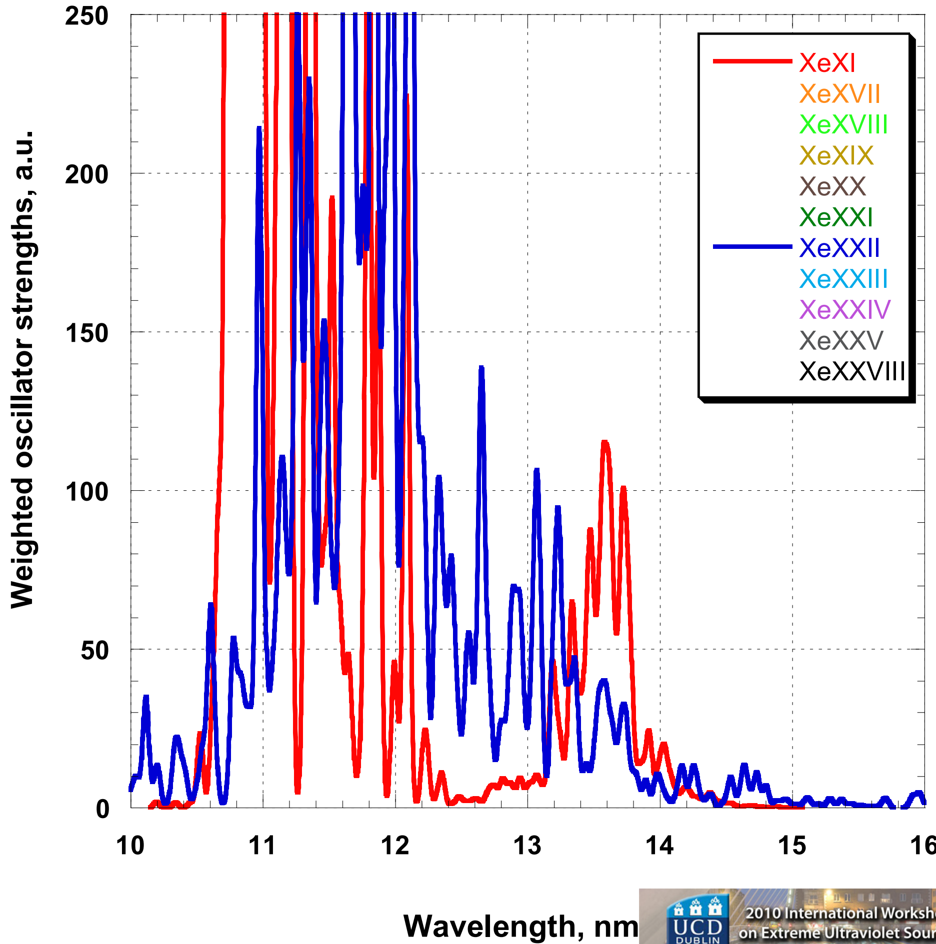
Xenon revisited

From XeXI to XeXIX -XeXXIV

XeXXI - XeXXV

produce also 4f-4d*, 4d-4p*, 5p-4d* ($4p^{n-1}4f^1 + 4p^{n-2}4d^2 + 4p^{n-1}5p^1 \rightarrow 4p^{n-1}4d^1$) satellites [White] in 2% bandwidth at 13-14nm spectral range





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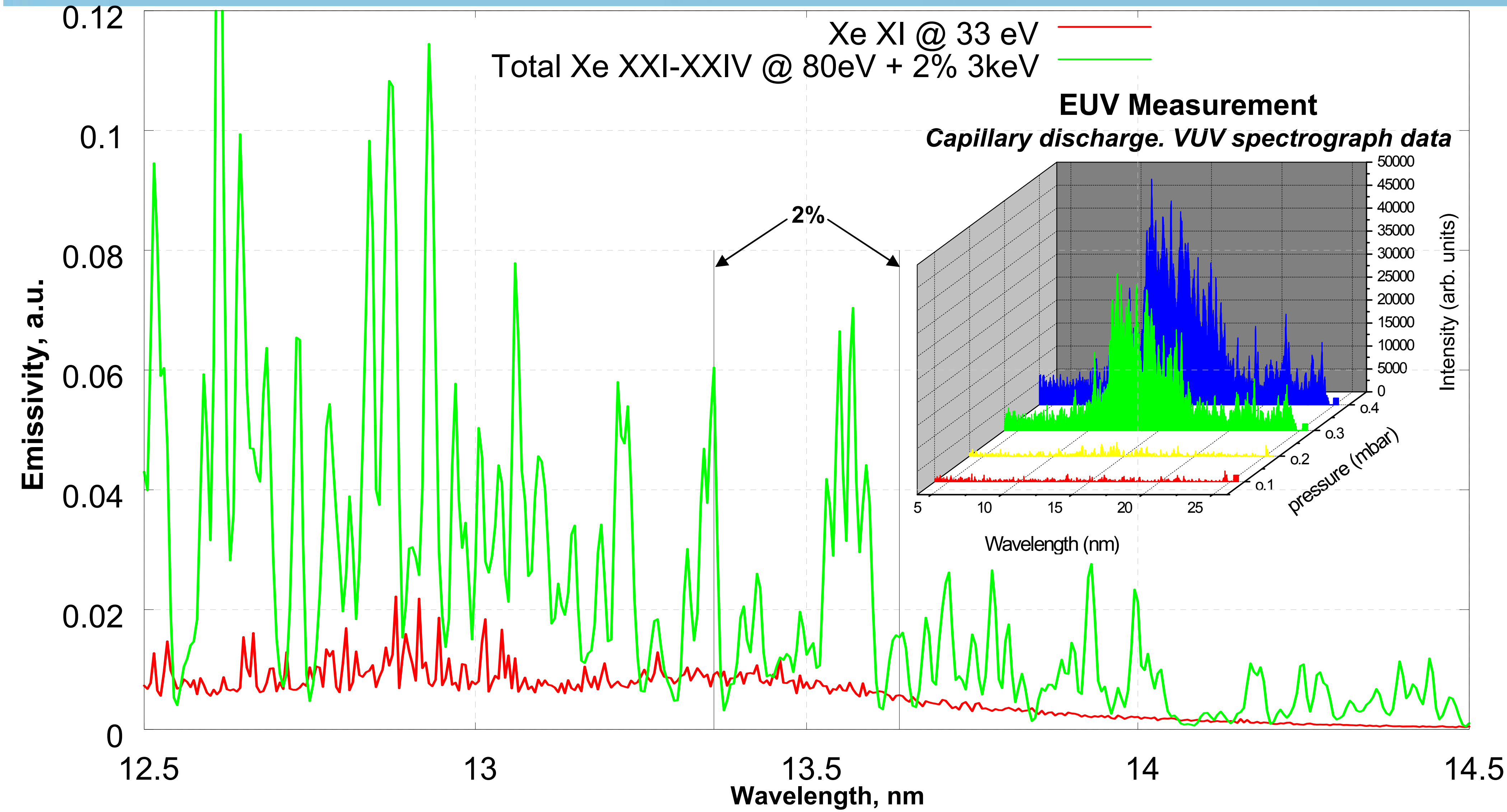
Non-equilibrium kinetic modeling

Total Emissivity of Xe XXI - Xe XXIV ions



Total EUV line emission spectra of Xe XXI - XXIV ions from non-equilibrium plasma at 80 eV with 2% of fast electrons at 3 keV in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (red). Electron density $N_e = 10^{17}$ 1/cm^3

EUV IF Power Limitation

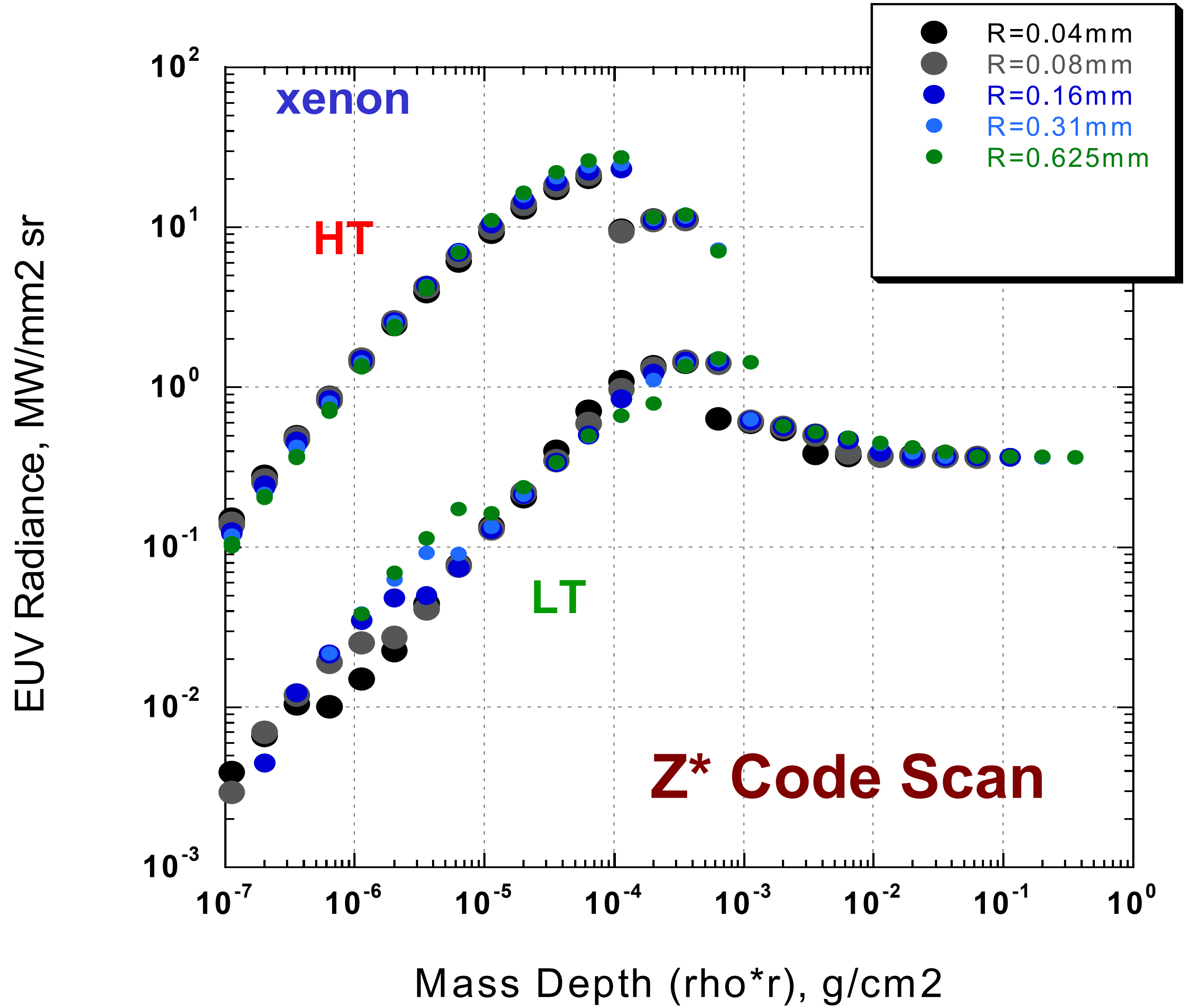
Two regimes in transparent plasma

There are two regimes in transparent plasma of xenon:

Low - Temperature (LT) with XeXI ion and

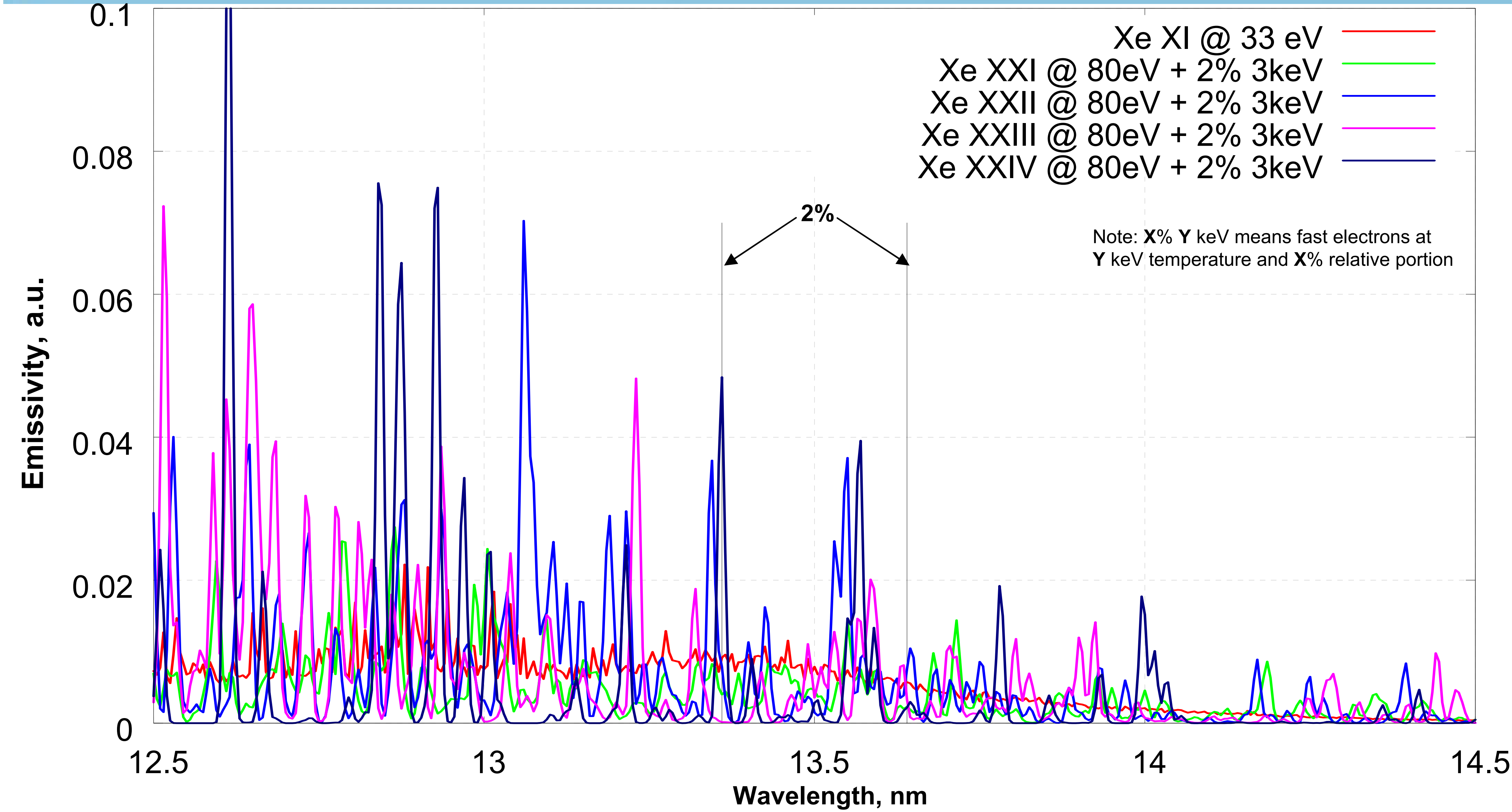
High - Temperature (HT) with XeXVII - XeXXIV ions contributing into 2% bandwidth in the spectral region 13-14nm.

For small size xenon plasma, the maximum EUV radiance in the HT can exceed the tin plasma emission



Non-equilibrium kinetic modeling

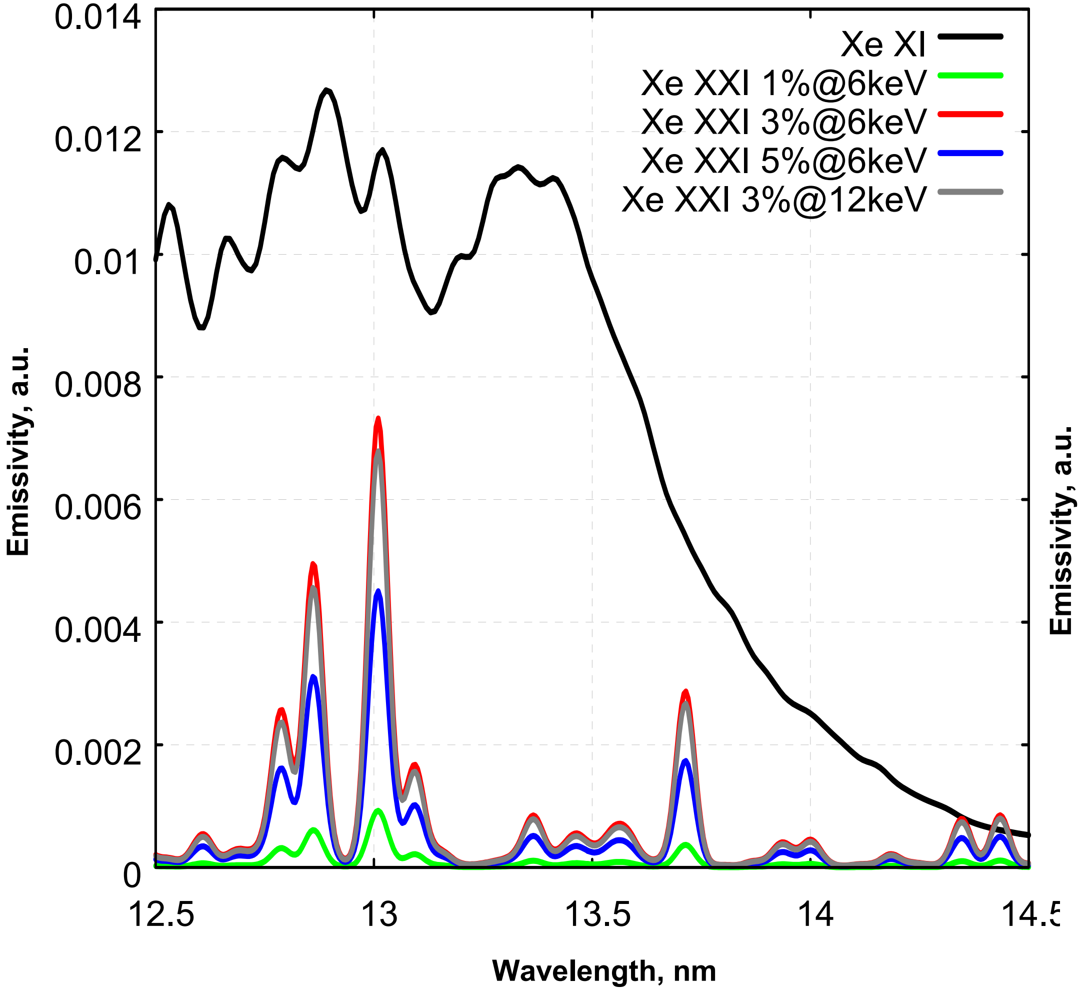
Emissivity of Xe XXI – Xe XXIV ions



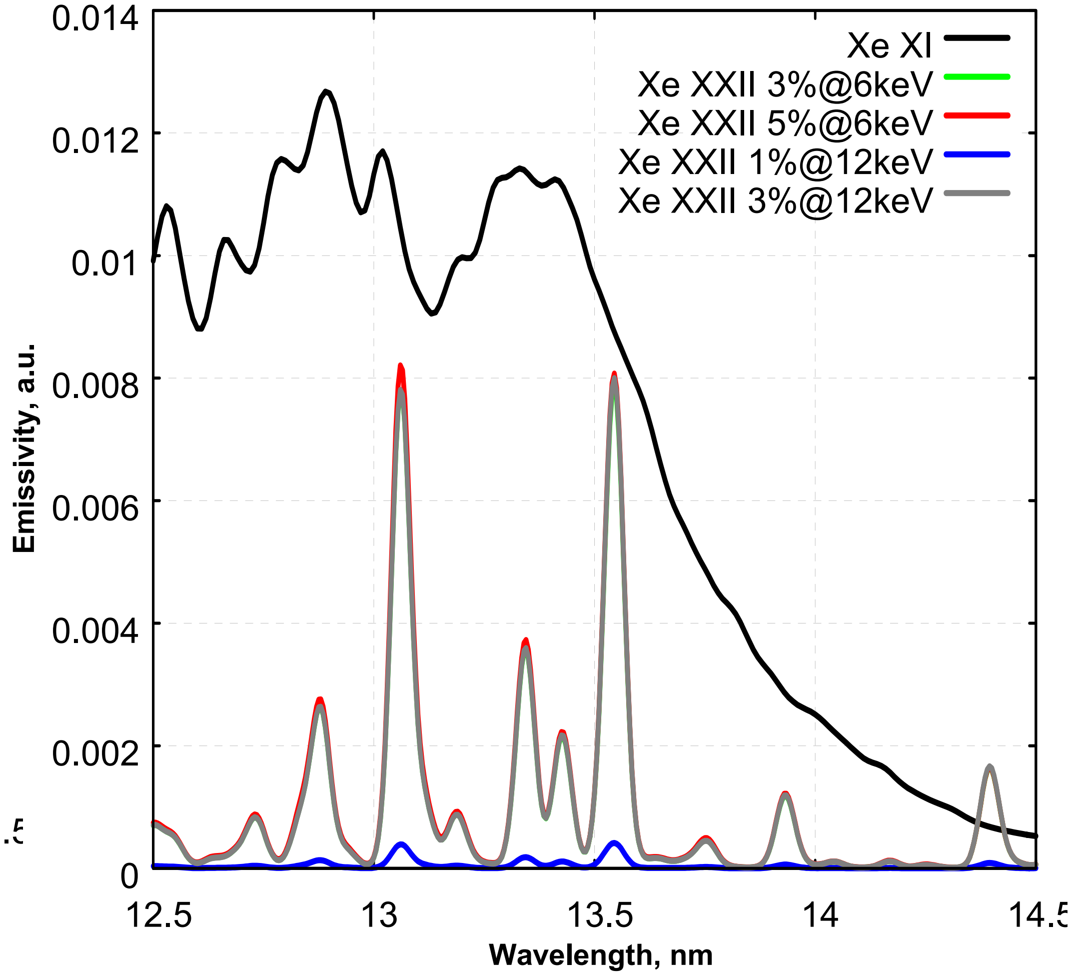
EUV line emission spectra of various Xenon ions from non-equlibrium plasma at 80 eV with 2% of fast electrons at 3 keV in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (red). Electron density is 10^{17} 1/cm^3

Non-equilibrium kinetic modeling

Emissivity of Xe XXI & XXII ions



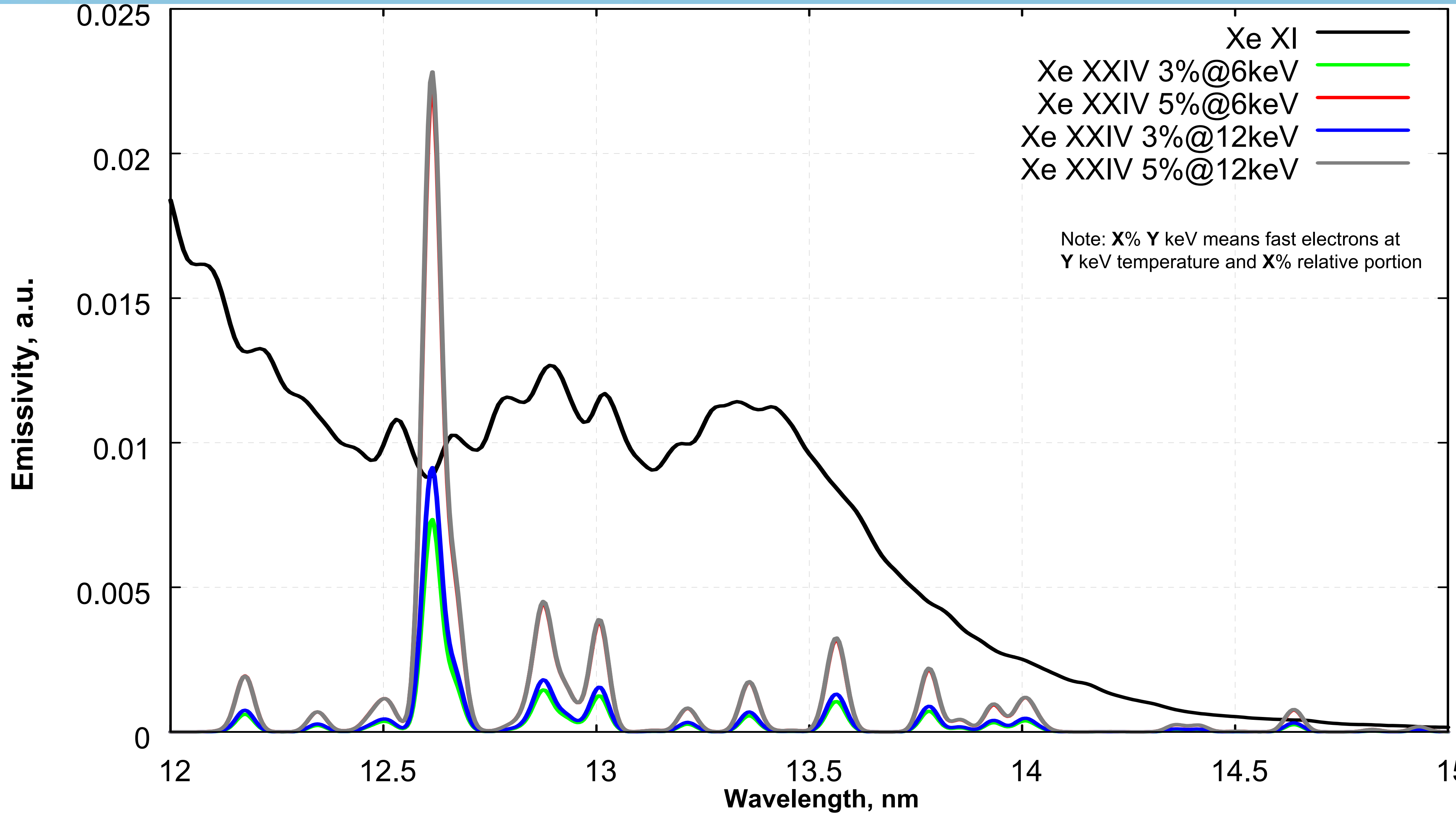
Note: **X**% **Y** keV means fast electrons at **Y** keV temperature and **X**% relative portion



EUV emission spectra of Xe XXI and XXII ions from non-equlibrium plasma at 30eV temperature with fast electrons at various temperature and percentage in comparison with emission spectrum of Xe XI ions from plasma at 30 eV (black). Electron density = 10^{17} 1/cm^3

Non-equilibrium kinetic modeling

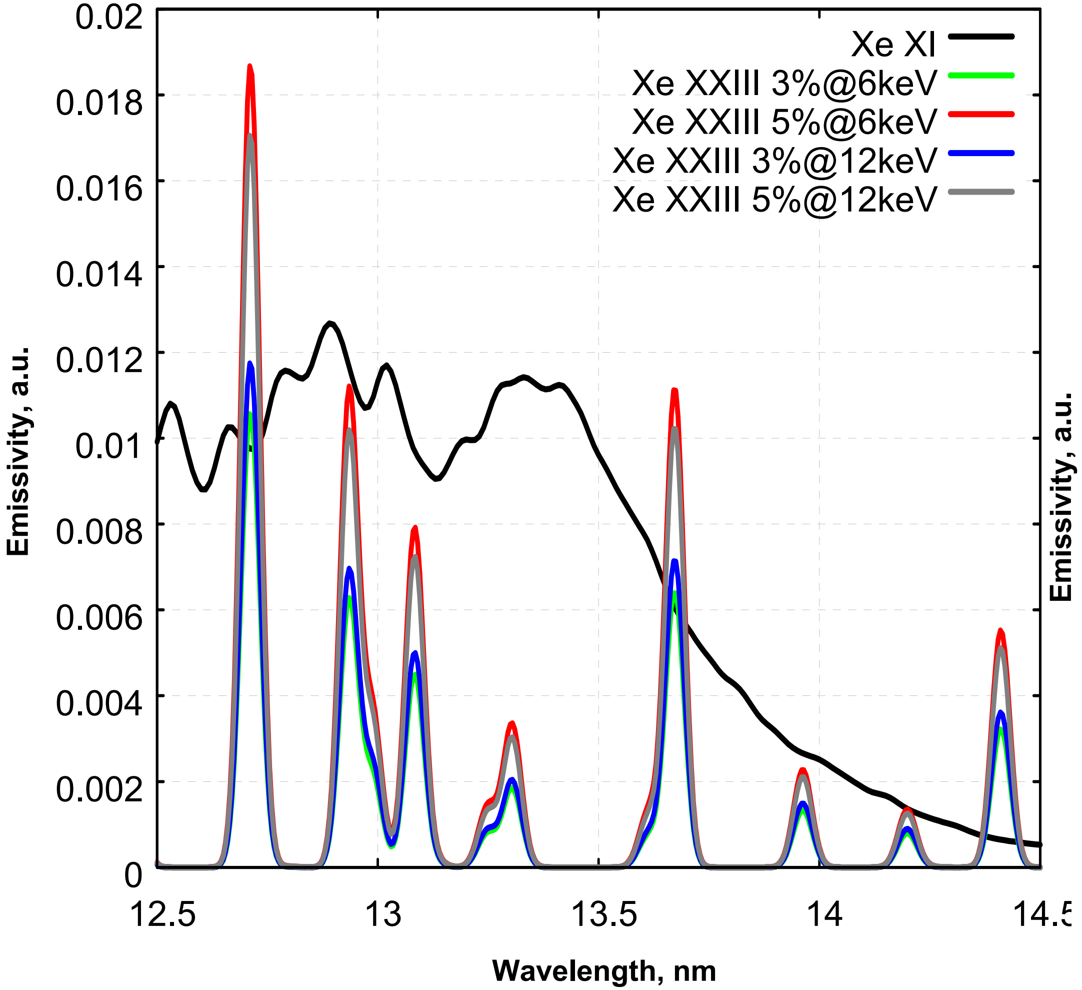
Emissivity of Xe XXIV ions



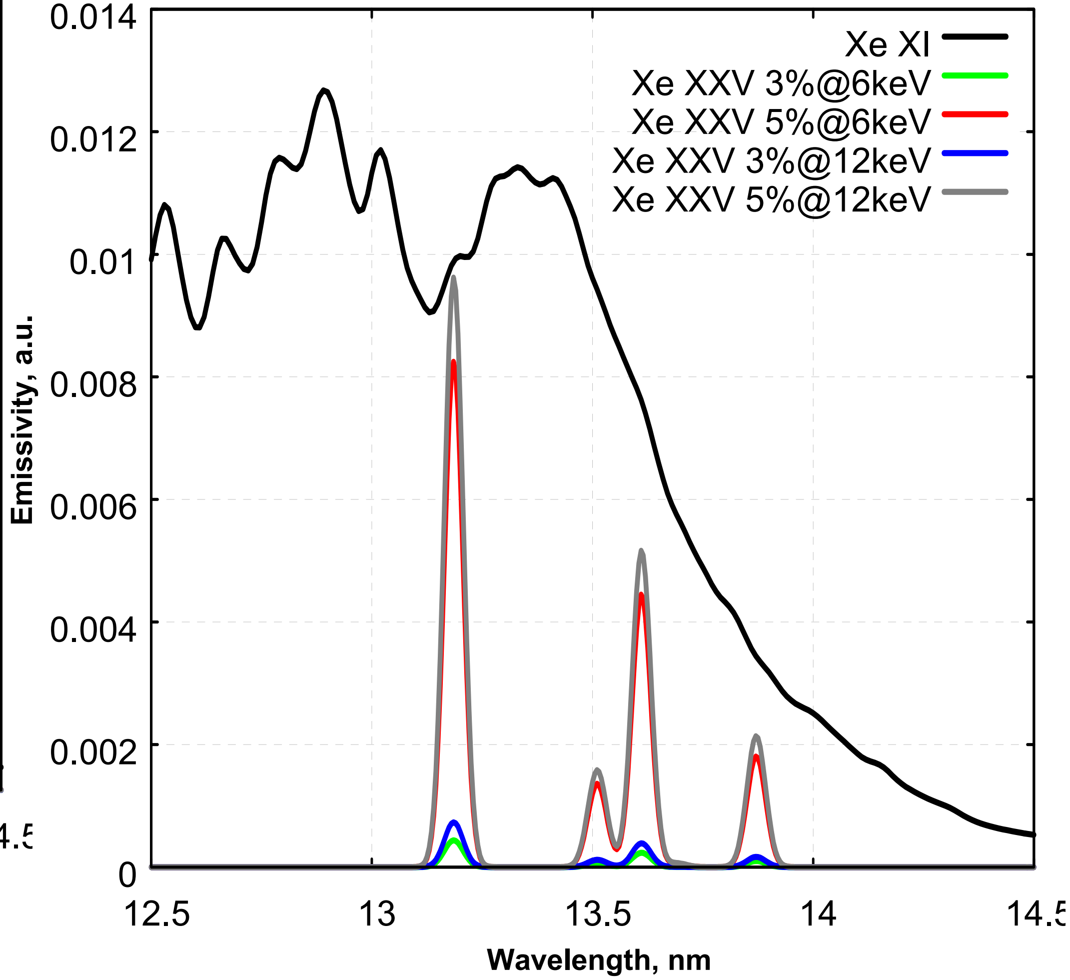
EUV emission spectra of Xe XXIV ions from non-equlibrium plasma at 30eV temperature with fast electrons at various temperature and percentage in comparison with emission spectrum of Xe XI ions from plasma at 30 eV (black). Electron density = 10^{17} 1/cm^3

Non-equilibrium kinetic modeling

Emissivity of Xe XXIII & Xe XXV ions



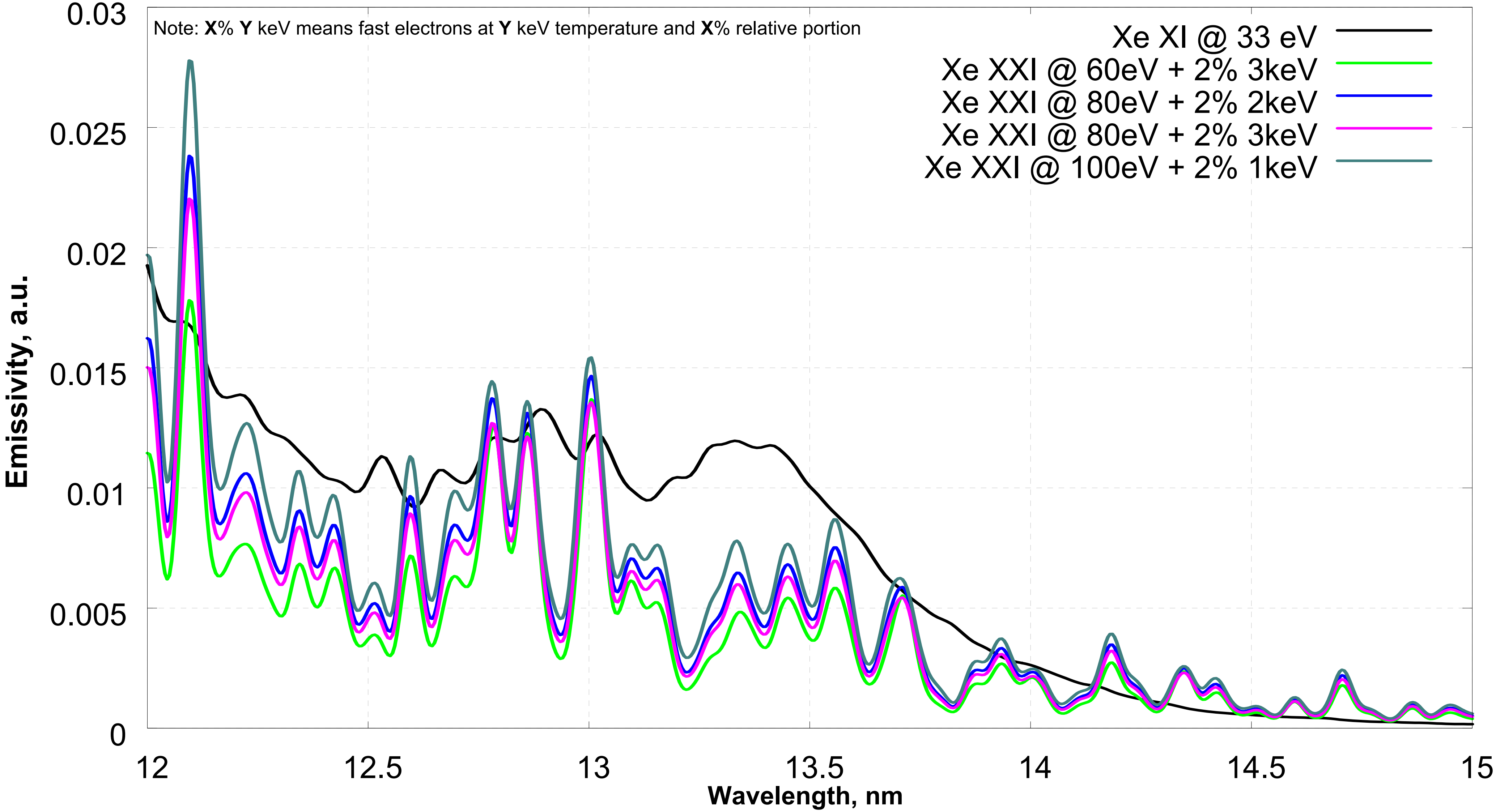
Note: **X**% **Y** keV means fast electrons at
Y keV temperature and **X**% relative portion



EUV emission spectra of Xe XXIII and XXV ions from non-equlibrium plasma at 30eV temperature with fast electrons at various temperature and percentage in comparison with emission spectrum of Xe XI ions from plasma at 30 eV (black). Electron density = 10^{17} 1/cm^3

Non-equilibrium kinetic modeling

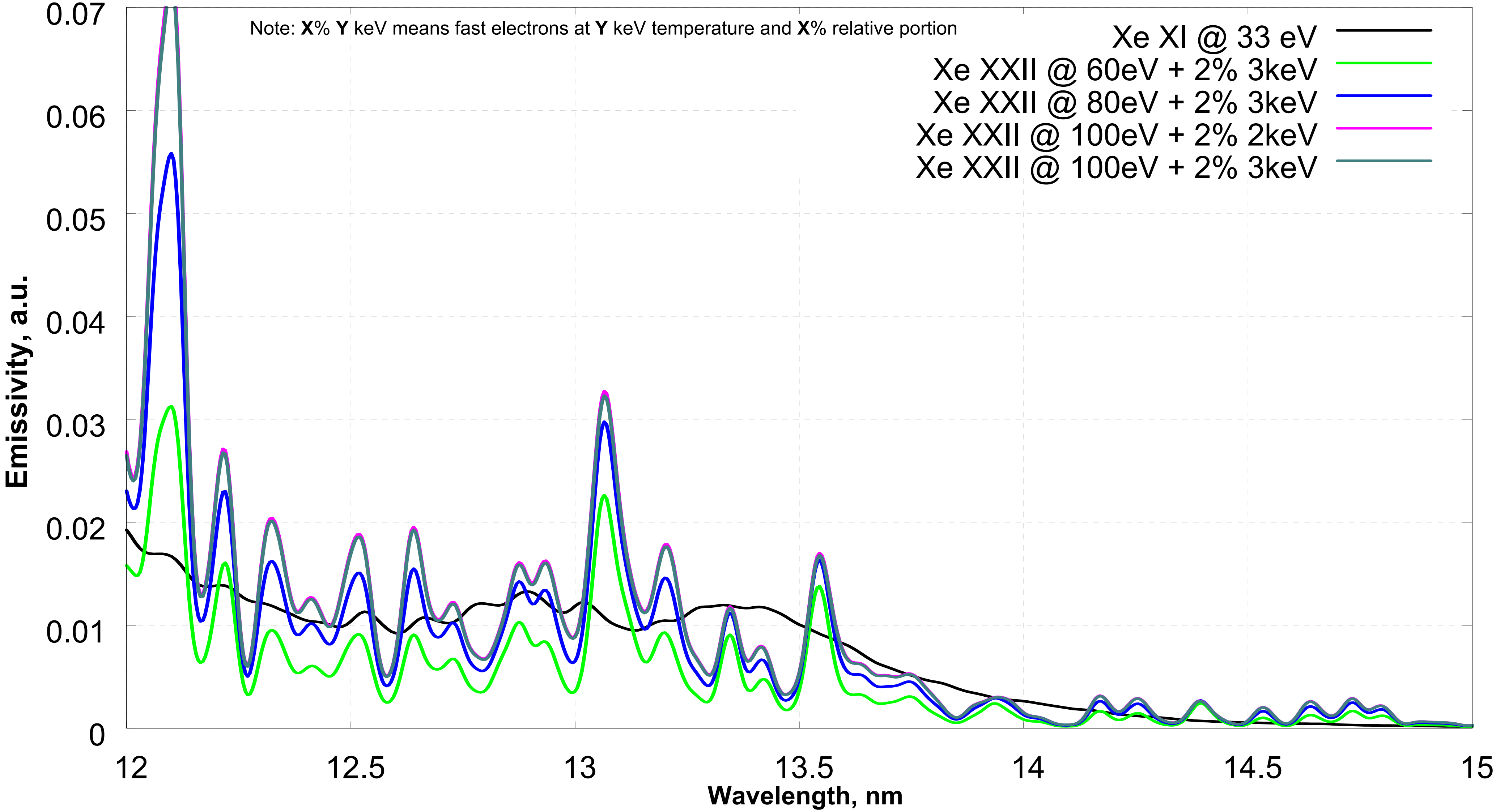
Emissivity of Xe XXI ions



EUV emission spectra of Xe XXI ions from non-equlibrium plasma with fast electrons under optimum conditions in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (black). Electron density = 10^{17} 1/cm^3

Non-equilibrium kinetic modeling

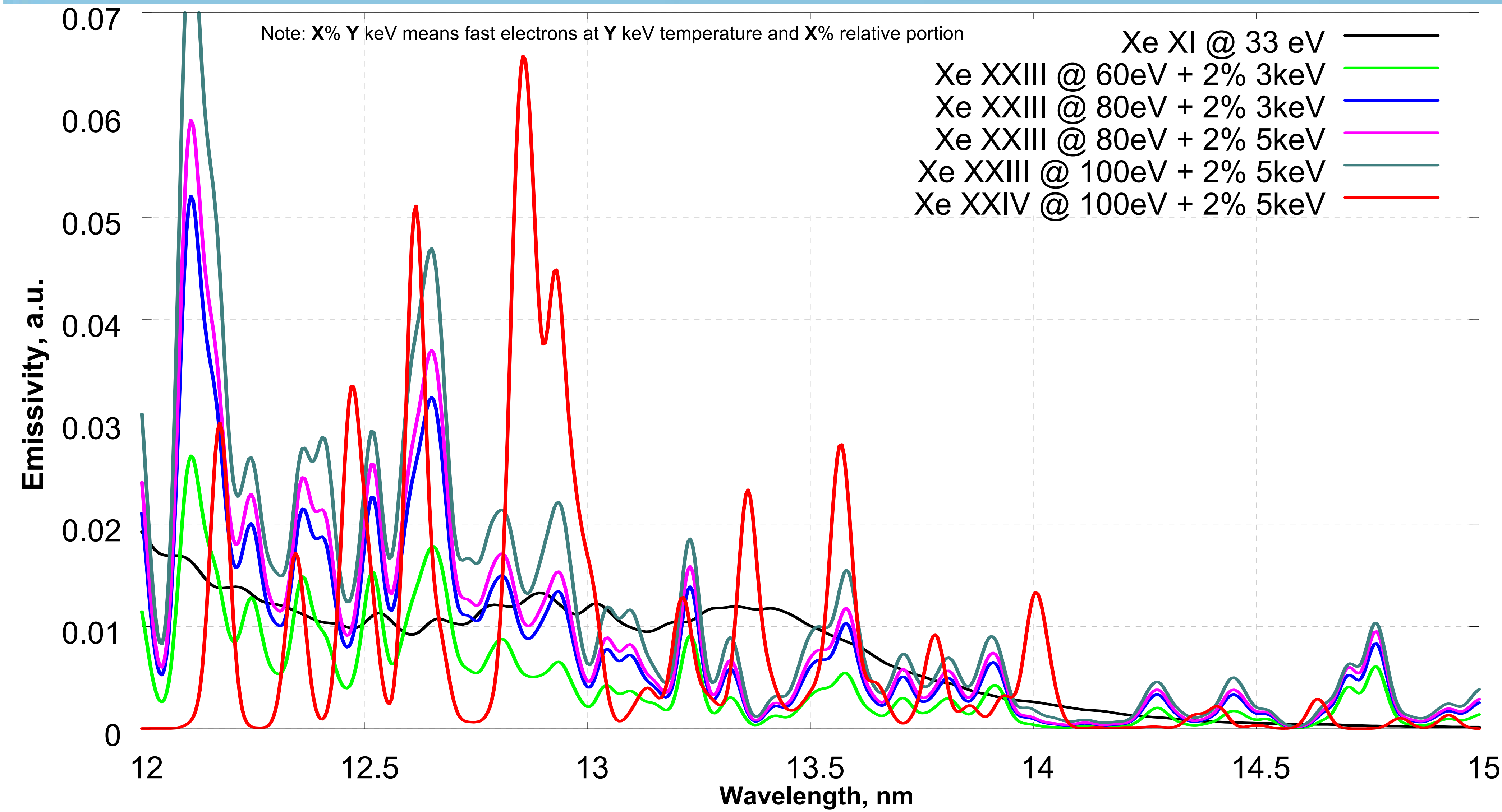
Emissivity of Xe XXII ions



EUV emission spectra of Xe XXII ions from non-equlibrium plasma with fast electrons under optimum conditions in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (black). Electron density = 10^{17} 1/cm^3

Non-equilibrium kinetic modeling

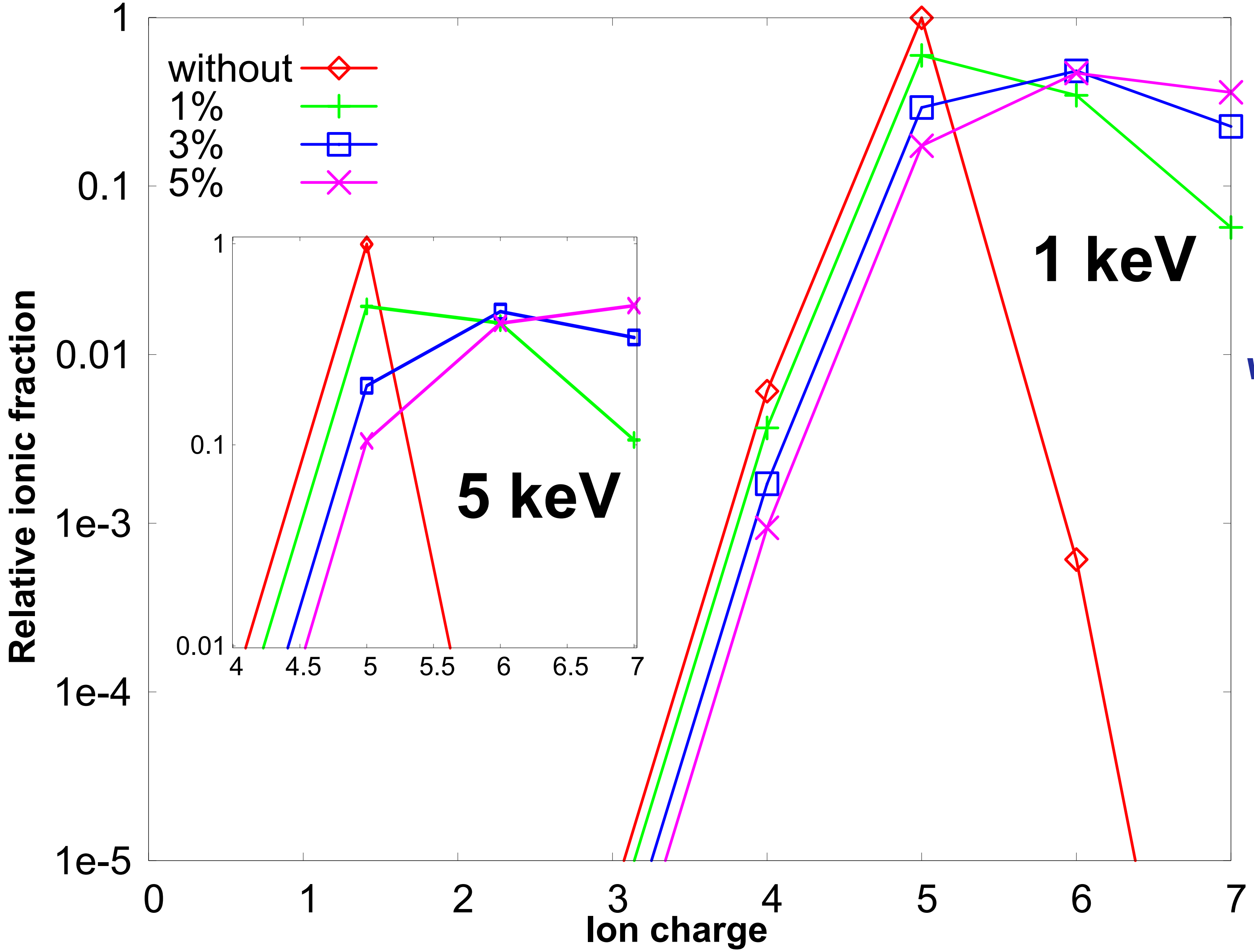
Emissivity of Xe XXIII & Xe XXIV ions



EUV emission spectra of Xe XXIII and Xe XXIV ions from non-equlibrium plasma with fast electrons under optimum conditions in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (black). Electron density = 10^{17} 1/cm^3

Non-equilibrium kinetic modeling

Ionic fractions



Calculated ionic fractions in Nitrogen plasma without and with fast electrons of 1keV and 5keV temperature and various percentage (1%-5%)

Temperature

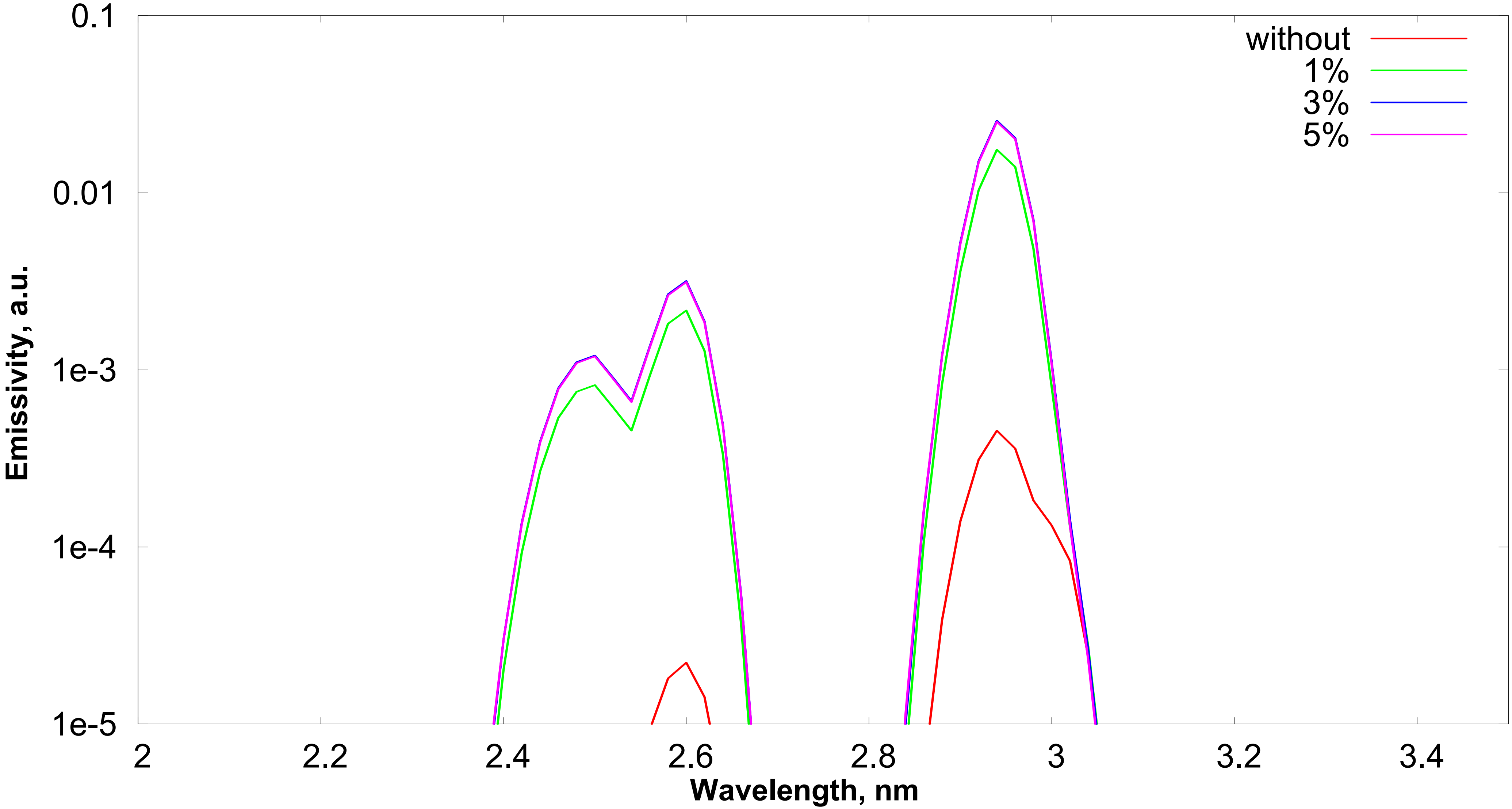
T = 45 eV

Electron density

$N_e = 10^{17}\ 1/cm^3$

Non-equilibrium kinetic modeling

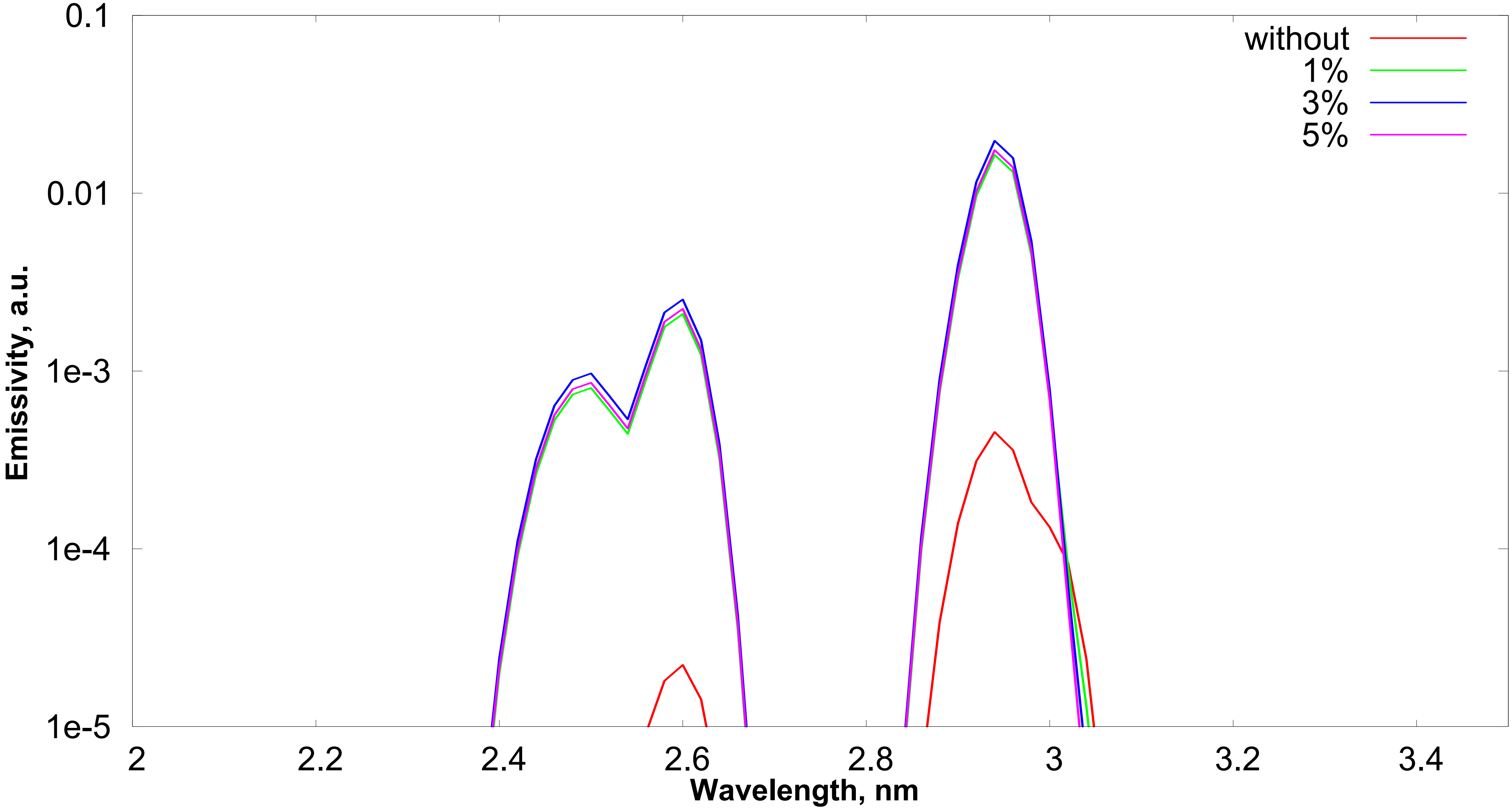
Total emissivity of nitrogen plasma



Total EUV line emission spectra of Nitrogen from non-equilibrium plasma at T=45 eV with various portions (1% to 5%) of fast electrons at 1 keV in comparison with emission spectrum of equilibrium plasma at the same temperature. Electron density N_e= 10^{17} 1/cm^3.

Non-equilibrium kinetic modeling

Total emissivity of nitrogen plasma



Total EUV line emission spectra of Nitrogen from non-equilibrium plasma at T=45 eV with various portions (1% to 5%) of fast electrons at 5 keV in comparison with emission spectrum of equilibrium plasma at the same temperature. Electron density N_e= 10^{17} 1/cm^{3}.

Summary

- Fast electrons have a considerable influence on the emission spectra and the line intensity values mostly due to increasing of the ion fractions and level populations

- Large part of EUV emission at 135Å may be achieved from highly charged Xe ions in plasma with addition of low portion of fast electrons

- Contribution from highly charged Xe ions depends strongly from parameters of plasma (it is not enough to shift ionization degree of plasma only)

- Soft X-ray emission from nitrogen plasma may be increased by addition of fast electrons due to the strong population growing of excited states

The results were obtained in frames of FP7 FIRE Marie Curie action